Spectrum of a Prototype Model with the Higgs as pNGB

Anna Hasenfratz[1], Claudio Rebbi[2*], Oliver Witzel[3]

[1]University of Colorado at Boulder, [2]Boston University, [3]University of Edinburgh, [*]presenter

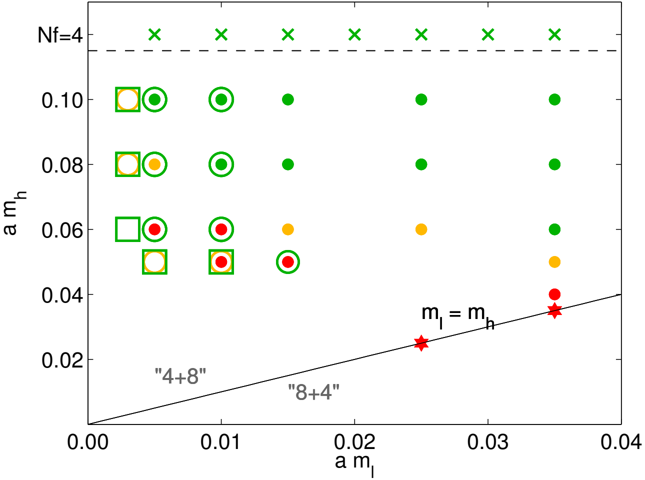
with Richard Brower and Evan Weinberg in the early stages of this work

Lattice 2016, Southhampton, July 25, 2016

The FourPlusEight simulations (computational details)

- 1 staggered field (= 4 flavors) with light mass m_ℓ plus 2 staggered fields (= 8 flavors) with heavy mass m_h. Simulations done with $am_\ell = 0.003, 0.005, 0.010, 0.015, 0.025, 0.035$, $am_h = 0.050, 0.060, 0.080, 0.100$.
- fundamental-adjoint gauge action with $\beta = 4, \beta_a = -\beta/4$ [Cheng et al. 2013][Cheng et al. 2014], nHYP smeared staggered fermions [Hasenfratz et al. 2007].
- lattice sizes mostly $24^3 \times 48$ and $32^3 \times 64$, but also $16^3 \times 32$ (exploratory), $36^3 \times 64$ and $48^3 \times 96$.
- lattice generations with hybrid MC with one Hasenbusch intermediate mass; most simulations/measurements performed with FUEL [J. Osborn]; most calculations done with USQCD SciDAC software on USQCD computers at Fermilab and NSF-MRI computers at MGHPCC.
- disconnected diagrams (for 0^{++}) computed with stochastic sources (6 sources, full color and time dilution, even-odd space dilution.)
- references: [JETP 120 (2015) 3, 423] [PoS Lattice2014 254] [CCP proceedings 2014] [PRD 93 (2016) 075028]

Color coded diagram of the simulations



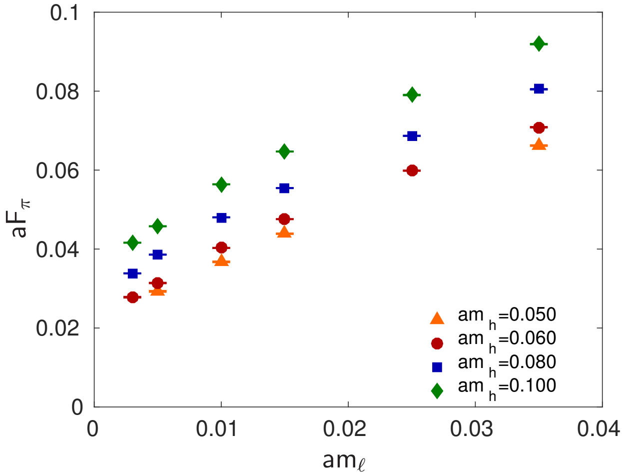
- Symbols indicate volumes and colors finite volume effects

  red: squeezed
  yellow: marginal
  green: OK

  □: $48^3 \times 96$ or $36^3 \times 64$
  ○: $32^3 \times 64$
  ●: $24^3 \times 48$

- Up to 40k MDTU

The pseudoscalar decay constant in lattice units

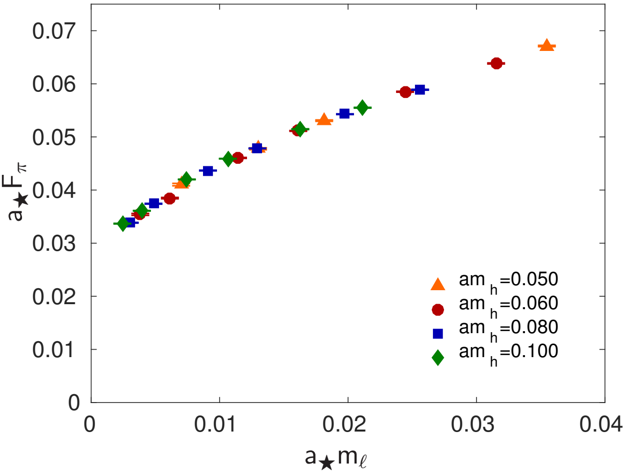


This highlights the importance of setting an appropriate scale.

Scale setting from the gradient flow

- Gradient flow defines the renormalized coupling:
  [Narayanan and Neuberger 2006] [Lüscher 2010]
  $g^2_{GF}(\mu = 1/\sqrt{8t}) = t^2\langle E(t)\rangle/\mathcal{N}$ (t: flow time; $E(t)$: action density.)
- g^2_{GF} is used for scale setting: $g^2_{GF}(t = t_0) = 0.3/\mathcal{N}$ ("t_0=scale").
- we denote by $a_\star$ the lattice spacing for the simulation on the $36^3 \times 64$ lattice with $am_\ell = 0.003, am_h = 0.080$; the mass symbols in our graphs denote physical, dimensionful masses, hence they are multiplied by $a_\star$ to show results in common lattice units.

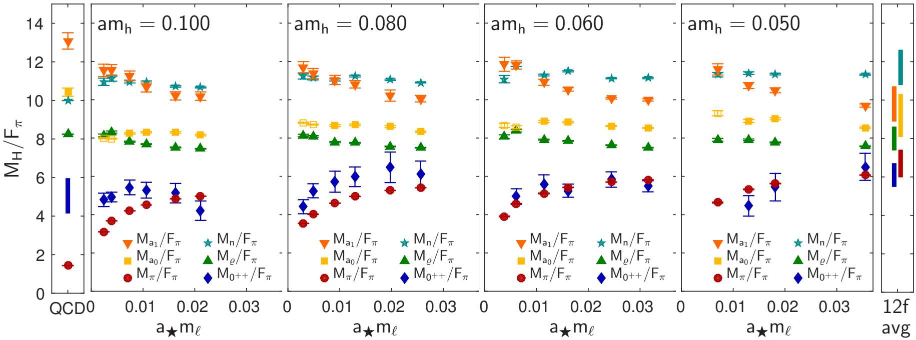
The pseudoscalar decay constant



After rescaling by the scale set through the Wilson flow the values of the pseudoscalar decay constants obtained with different light and heavy masses all line up nicely on a single curve.

Spectrum of light fermion composite states

from [PRD 93 (2016) 075028]



Observations:

0^{++} is light ($M_{0^{++}} < M_\rho$), it tracks the pion.

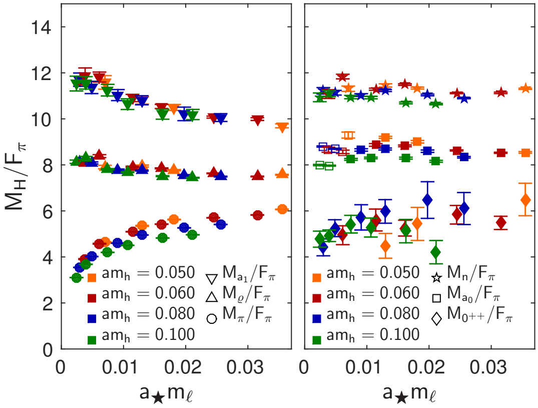
M_π/F_π bends down indicating that the system is chirally broken.

For growing m_h and $m_\ell \to 0$ the system approaches QCD, for decreasing m_h and $m_\ell \sim m_h$ we approach degenerate 12 flavors.

The ratios appear largely independent of m_h!

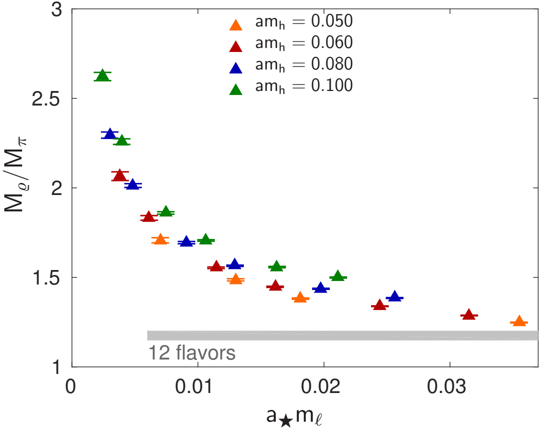
Hyperscaling in the light mass spectrum

from [PRD 93 (2016) 075028]



- $M_n/F_\pi \approx 11$
- $M_\varrho/F_\pi \approx 8$
- $M_{0^{++}}/F_\pi \approx 4-5$ (taking the chiral limit is difficult but 0^{++} well separated from the ϱ)

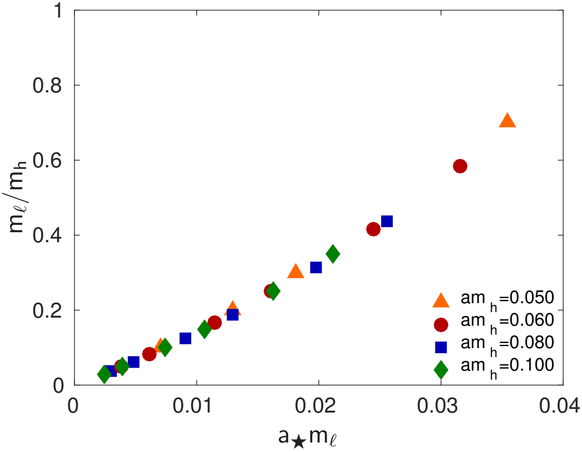
The system is chirally broken



- In 4 flavors (QCD-like) we know the ratio diverges
- In 12 flavors an almost constant ratio is observed [Cheng at al. 2014]

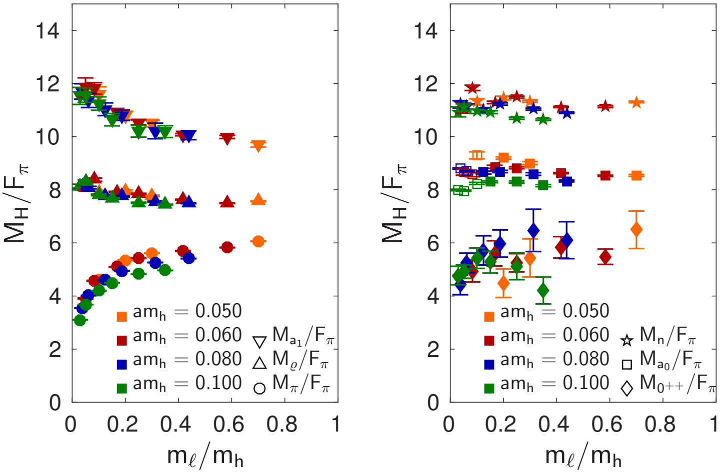
— as expected for conformal systems

Expressing observables as functions of m_ℓ/m_h



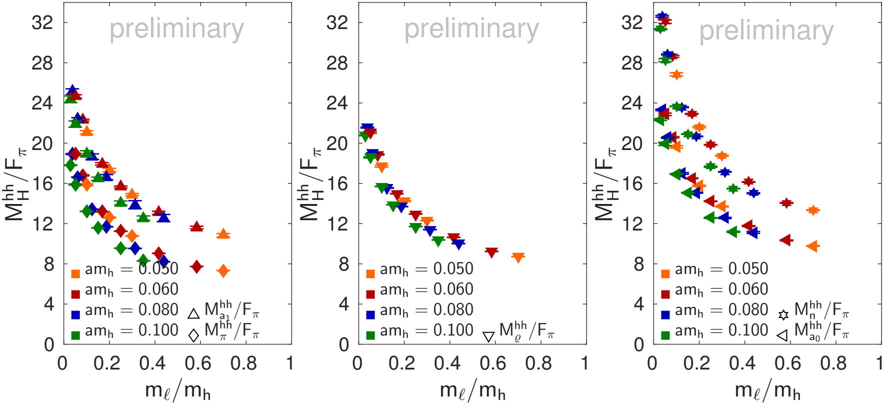
As shown by Anna Hasenfratz in the previous talk observables depend only on the ratios m_ℓ/m_h and not on m_ℓ or m_h individually. m_ℓ/m_h tracks indeed $a_\star m_\ell$ and will be used to label the horizontal axis in the following graphs.

Hyperscaling in the light mass spectrum

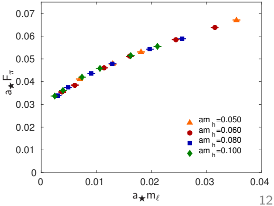


expressing observables as functions of m_ℓ/m_h.

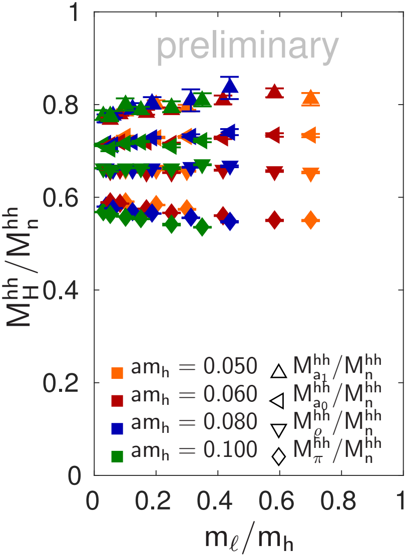
Hyperscaling in the spectrum of heavy fermion composites



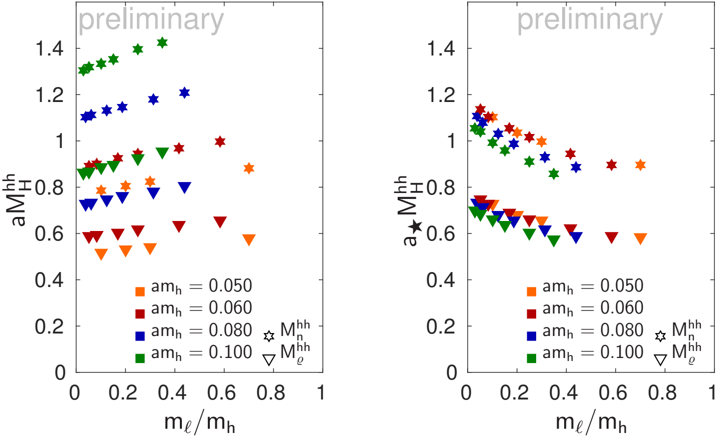
The increase of the ratios M_H^{hh}/F_π for $a_\star m_\ell \to 0$ is due to the decrease of F_π, which tends to a small but non-zero value in the same limit. To the extent that $F_\pi(m_\ell = 0)$ set the EW scale the high values of the ratios have physics significance.



The heavy fermion spectrum vs. the heavy nucleon mass



Effect of scale setting for the masss of the heavy N and ρ



The left frame shows the the heavy N and ρ masses in the original lattice units, the right frame shows the same masses after the mass scale has been set through the Wilson flow.

Conclusions

- Our results provide strong evidence for hyperscaling in the heavy fermion masses.
- There is some analogy between m_h in our model and the bare coupling constant g in QCD: near the fixed point the physicsl values of masses and other observables do not depend on them, changing their value only varies the domain of scaling (in QCD lowering g increases the high energy cut-off, here lowering m_h increases the domain of walking)
- The values of the observables will, however, depend on the model, and if the theory of EW symmetry breaking is to be found, indeed, in a strong dynamics framework, experiment and theory will decide which is the correct model.